

Searches for $t\bar{t}HH$ production with the ATLAS detector

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o.b.o the *ATLAS Collaboration*

arXiv:2603.13113

THE 3RD DI-HIGGS PRODUCTION MODE - $t\bar{t}HH$

At 13.6 TeV at LHC

52 340 fb

$ggF - H$

÷1500

34.13 fb

$ggF - HH$

÷20

1.87 fb

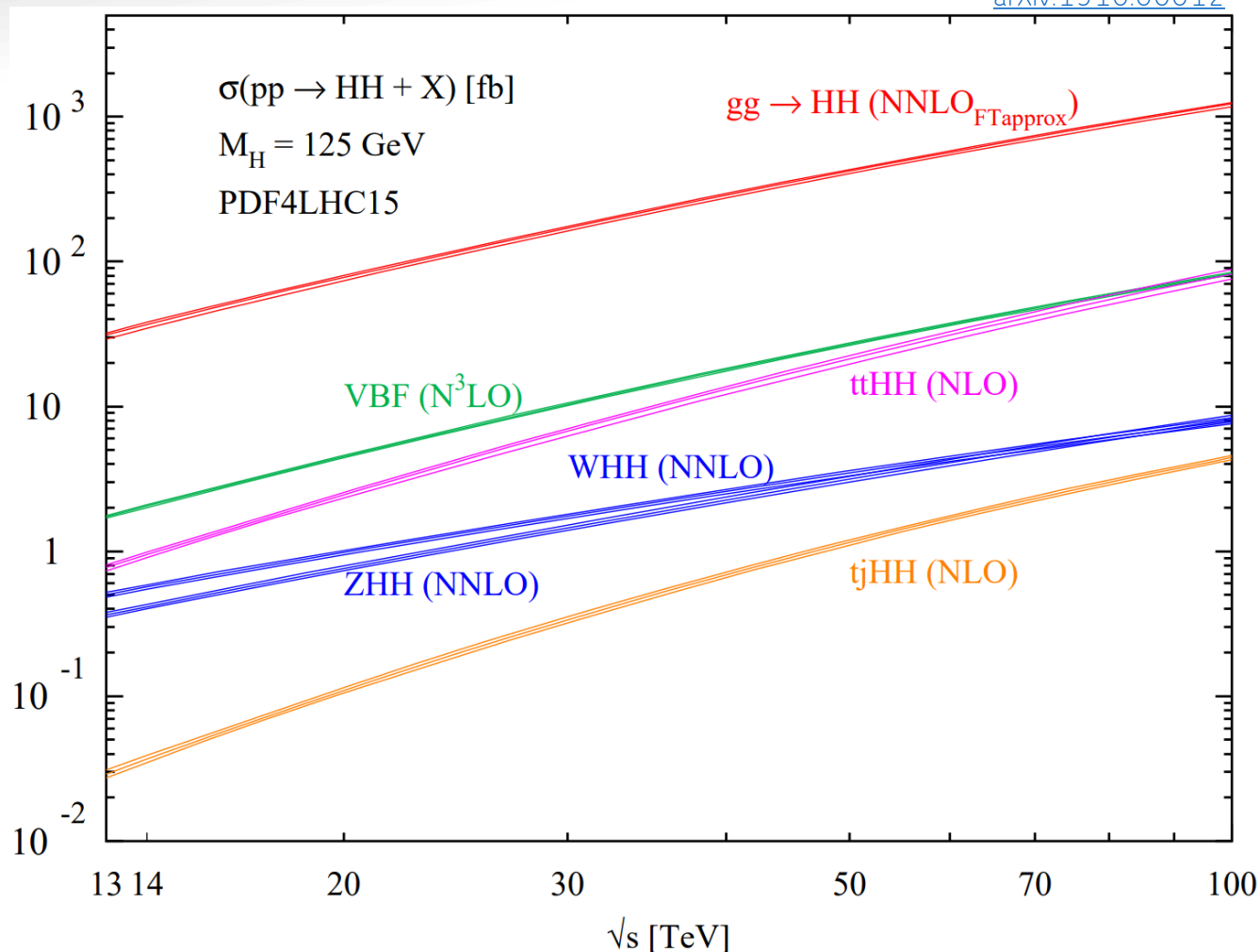
$VBF - HH$

÷2

0.87 fb

$t\bar{t}HH$

[arXiv:1910.00012](https://arxiv.org/abs/1910.00012)



Linking Higgs and top sectors



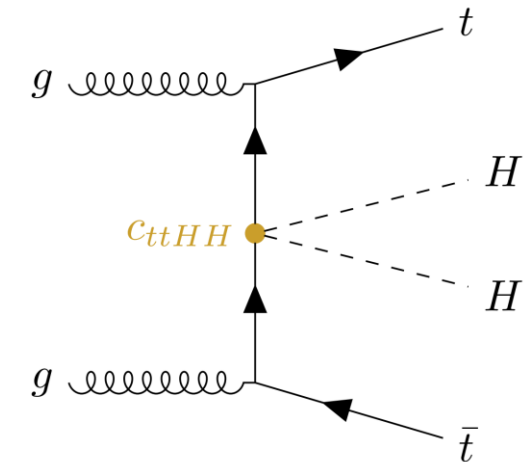
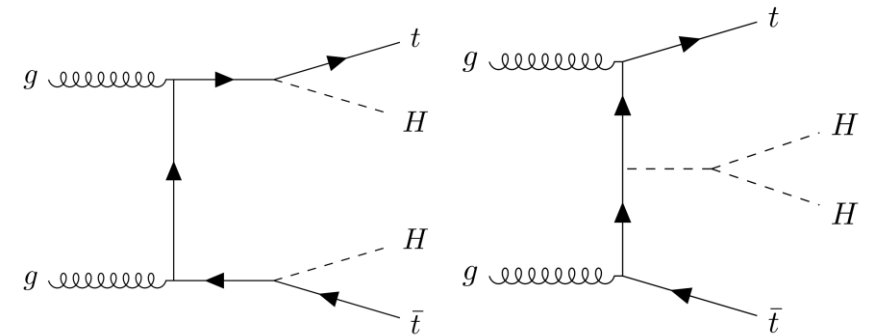
THE 1ST ATLAS SEARCH

3 final states combined with 196 fb^{-1}
to measure $t\bar{t}HH$ signal strength, μ

- 1L: Single lepton } $HH \rightarrow b\bar{b}b\bar{b}$
- SSML: Same sign multi-lepton } $HH \rightarrow b\bar{b} + [ZZ, \tau\tau, WW]$
→ non all-hadronic HH decays
- $b\bar{b}\gamma\gamma$ } $HH \rightarrow b\bar{b}\gamma\gamma$
→ Included in CMS preliminary result ([CMS-PAS-HIG-23-004](#))

Access to 3 couplings

- Unique BSM phase space
- EFT constraints
- Direct access to $C_{t\bar{t}HH}$



ANALYSIS STRATEGY OVERVIEW

THE DATA HARVEST AND STRATEGIES

• Integrated Luminosity & Triggers

Run 2 (13 TeV)
 $140.1 \pm 1.2 \text{ fb}^{-1}$

+

Run 3 (13.6 TeV)
 $56.0 \pm 1.1 \text{ fb}^{-1}$

- 1L/SSML: single-lepton triggers with p_T thresholds as low as 20-26 GeV
- $b\bar{b}\gamma\gamma$: diphoton triggers with 35 (25) GeV p_T thresholds for (sub-)leading photon

• Strategies overview

Event selection

CR/SR

Statistical inference

1L

1 lepton
4 b-jets
+ kinematic selections

Split by b-tag multiplicity

– GAT →

Binned fit on GAT score
*Graph Attention Network (GAT)

SSML

≥ 2 same-sign leptons
+ kinematic selections

Split by lepton multiplicity
(SS2L & 3L)
+ background type

– GAT →

Binned fit on GAT score

$b\bar{b}\gamma\gamma$

2 photons
 ≥ 3 b-jets
+ kinematic selections

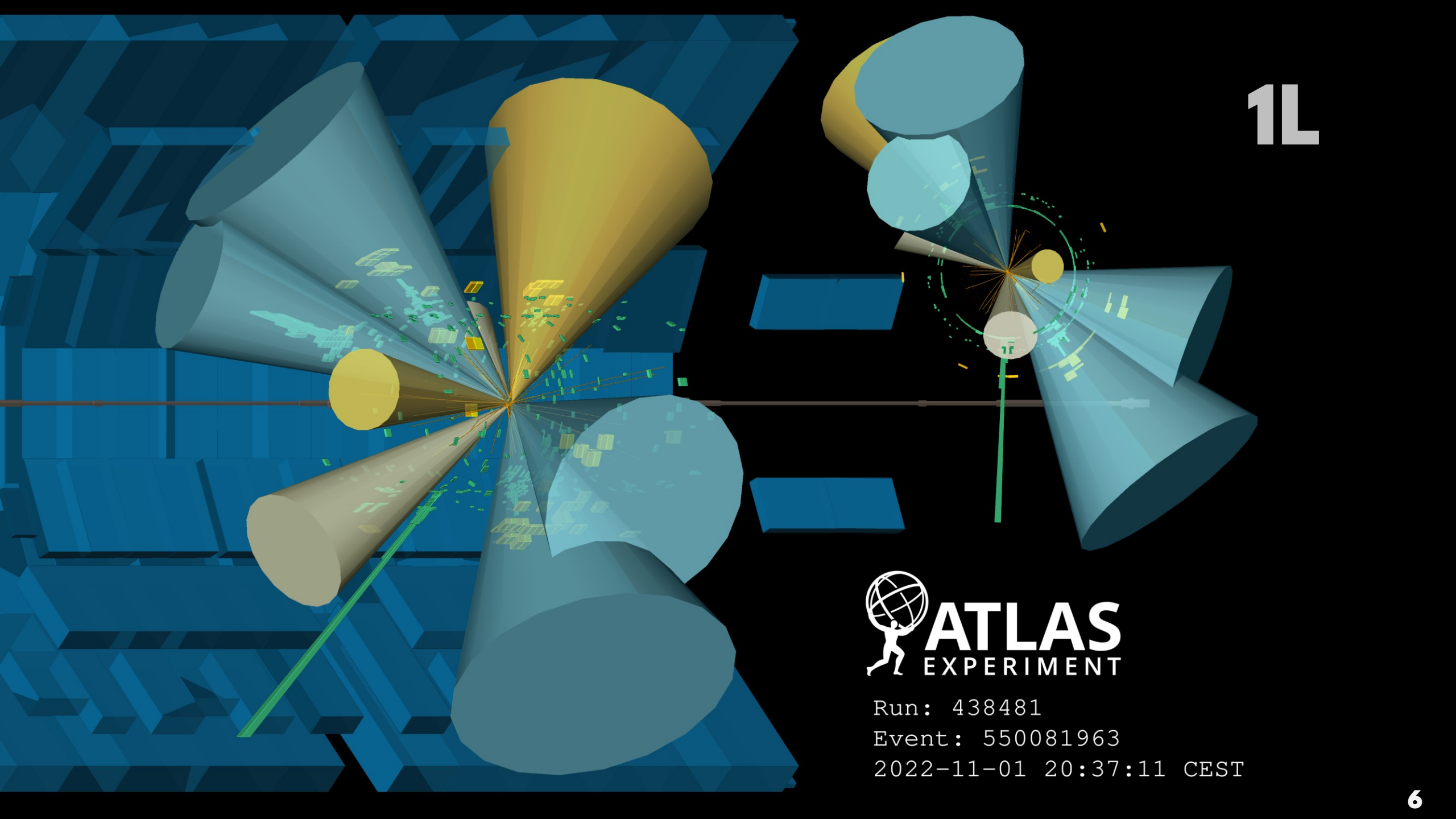
Split by MVA score thresholds
+ $m_{\gamma\gamma}$

– BDT →

Unbinned fit on $m_{\gamma\gamma}$



1L



 **ATLAS**
EXPERIMENT

Run: 438481

Event: 550081963

2022-11-01 20:37:11 CEST

THE 1L BACKGROUND MODELLING

• The Topology

1 lepton from W and ≥ 4 b – jets \rightarrow 20% of decays

• Taming the $t\bar{t}$ + HF Background

- Dominant background $t\bar{t}$ + jets, particularly $t\bar{t}$ + b/c production

• Truth-flavor categorization

- Samples divided according to extra HF content
 - $t\bar{t}$ + 1/2/3/ $\geq 4b$ and $t\bar{t}$ + 1 $c/light$
- Each of this components as a separate physical process
 - Independent modelling uncertainties
 - Independent normalization

• Data-driven normalization

- The dominant $t\bar{t}$ + 1/2 b components are left free in the fit
- Conservative uncertainty for rare $t\bar{t}$ + $\geq 3b$ (lack of the statistical power)

Kinematic selections

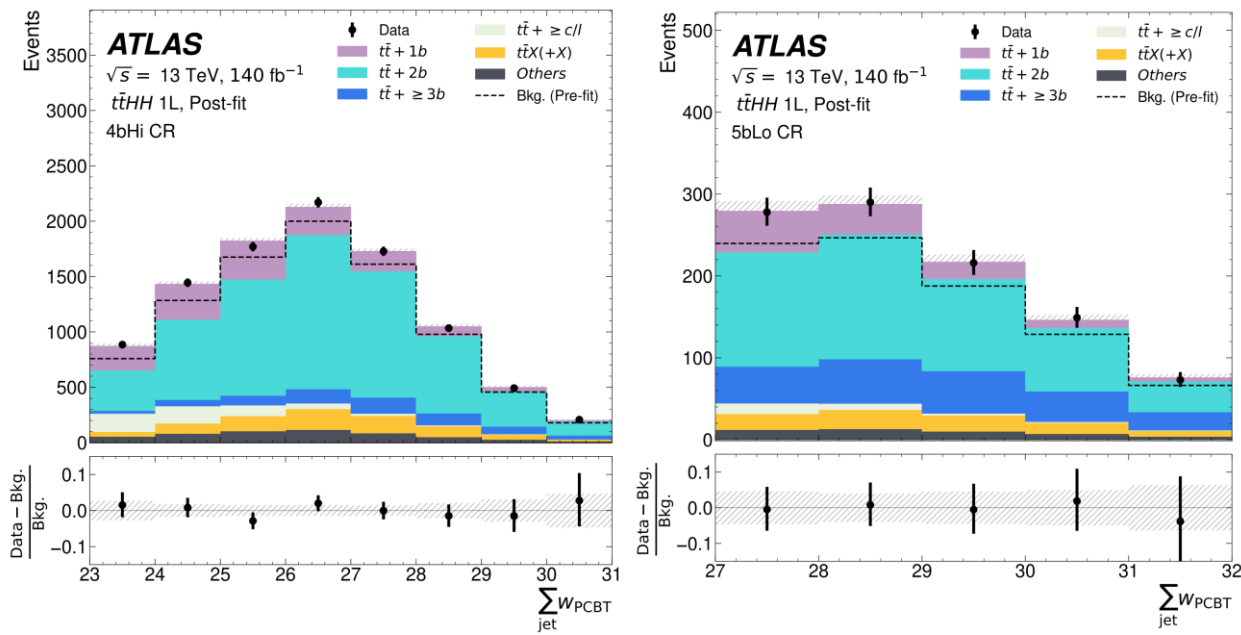
High momentum	$p_T > 27 \text{ GeV}$
Missing transverse momentum	$E_T^{\text{miss}} > 20 \text{ GeV}$
Large hadronic energy	$H_T > 400 \text{ GeV}$
High jet multiplicity	$6 \leq n_{\text{jets}} \leq 11$
b-tagged jet WP	85%



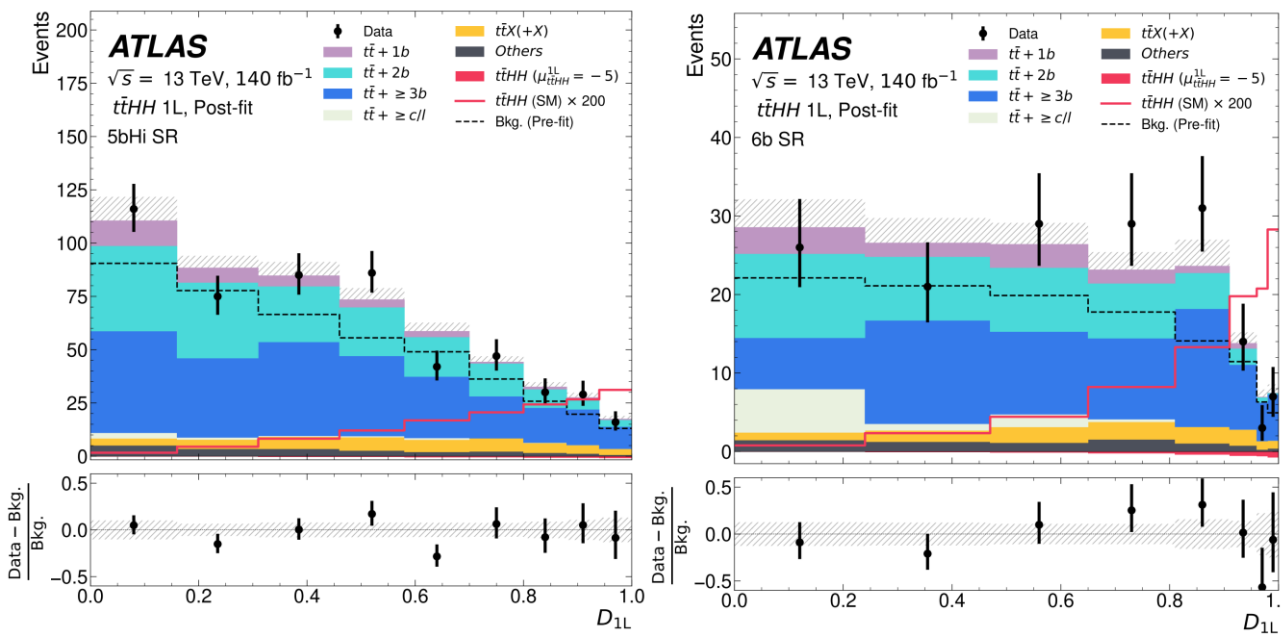
POST-FIT RESULTS

First-ever measurement

Control Regions



95% CLs limit
 $\mu_{1L} < 26$



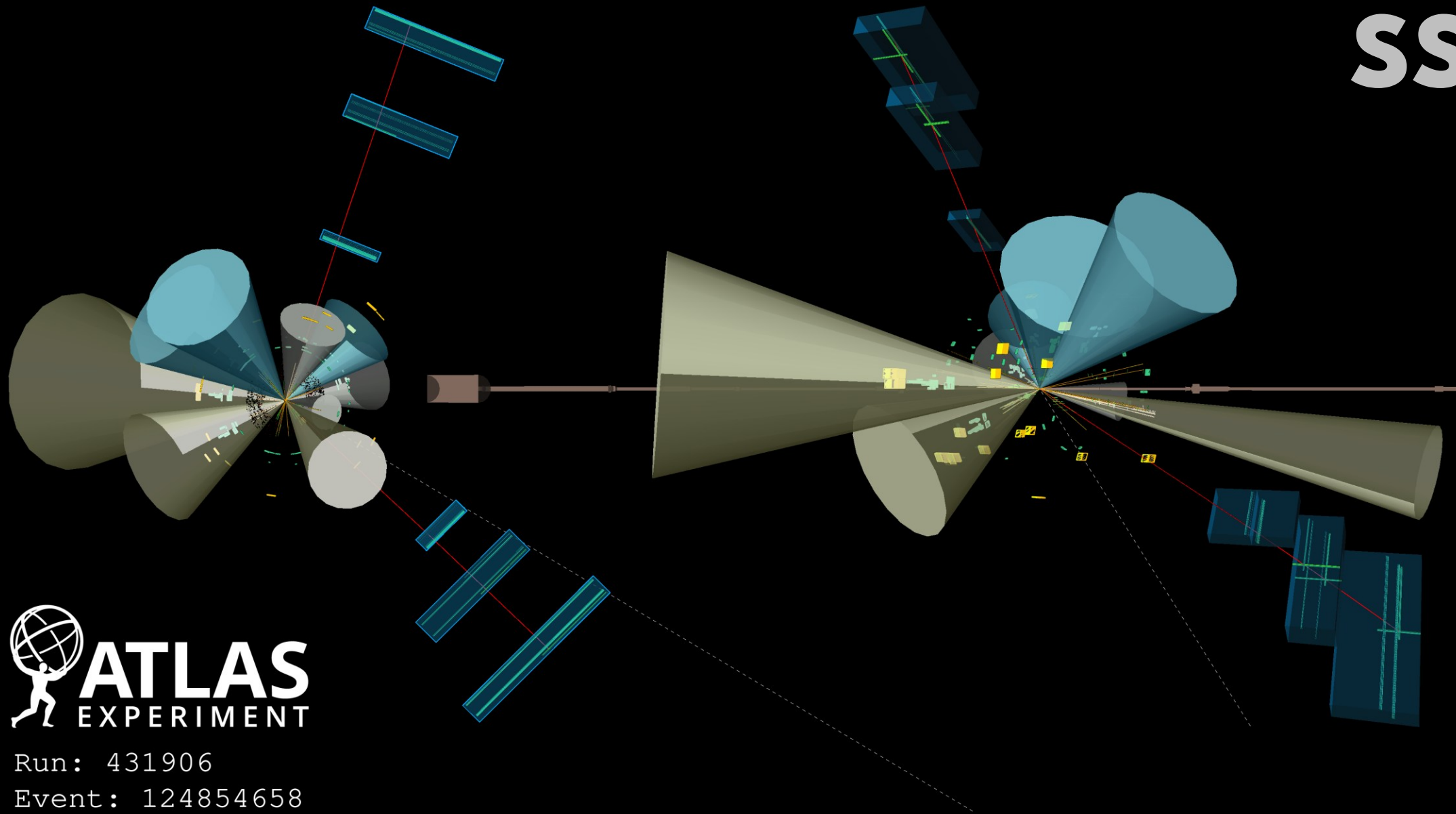
- Stable Data-Driven NF for dominant HF background
- Run 2 & Run 3 Consistency

Background source	Normalisation factor	
	Run 2	Run 3
$t\bar{t} + 1b$	$1.18^{+0.40}_{-0.35}$	
$t\bar{t} + 2b$	$0.91^{+0.11}_{-0.10}$	

Signal Regions



SSML



 **ATLAS**
EXPERIMENT

Run: 431906

Event: 124854658

2022-08-21 09:42:21 CEST

THE SSML BACKGROUND MODELLING

• Topology

$\geq 2b$ and ≥ 2 same-sign leptons from top and Higgs \rightarrow 7% of decays

• Irreducible prompt-lepton backgrounds

• $t\bar{t}W$ normalization

- Normalization constrained directly from data
- Template fit to N_{jet} \rightarrow corrects mismodelling at high multiplicities

• $t\bar{t}t\bar{t}$ background

- Conservative asymmetric normalization uncertainty +70%/-15%
- Covers theoretical uncertainties and recent experimental measurements

• Instrumental backgrounds

• Non-prompt / fake leptons from HF decays or photon conversions

- Semi-data-driven template fits across dedicated CR

• Charge mis-identification

- Derived from $Z \rightarrow ee$ events in data
- Parameterized as a function of lepton p_T and η

Kinematic selections

High momentum (subleading)	$p_T > 27 (15) GeV$
Large hadronic energy	$H_T > 400 GeV$
High jet multiplicity	$n_{jets} \geq 6 (SS2L)$ $n_{jets} \geq 5 (3L)$
Z-boson veto	$ m_{\ell\ell} - m_Z > 10 GeV$
b-tagged jet WP	85%

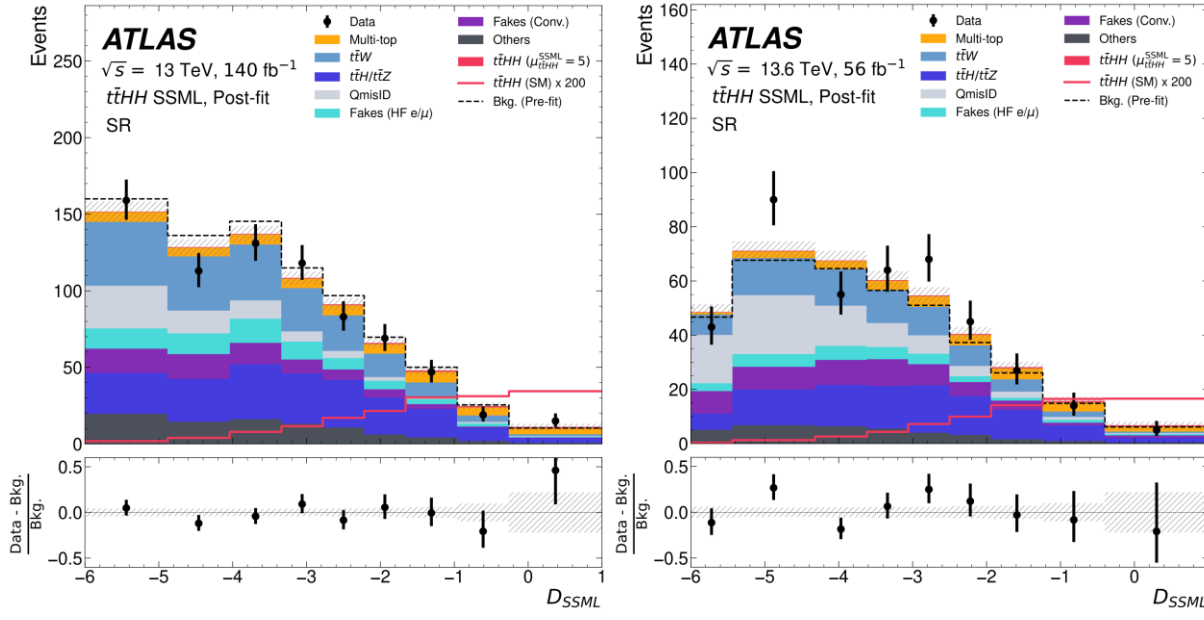
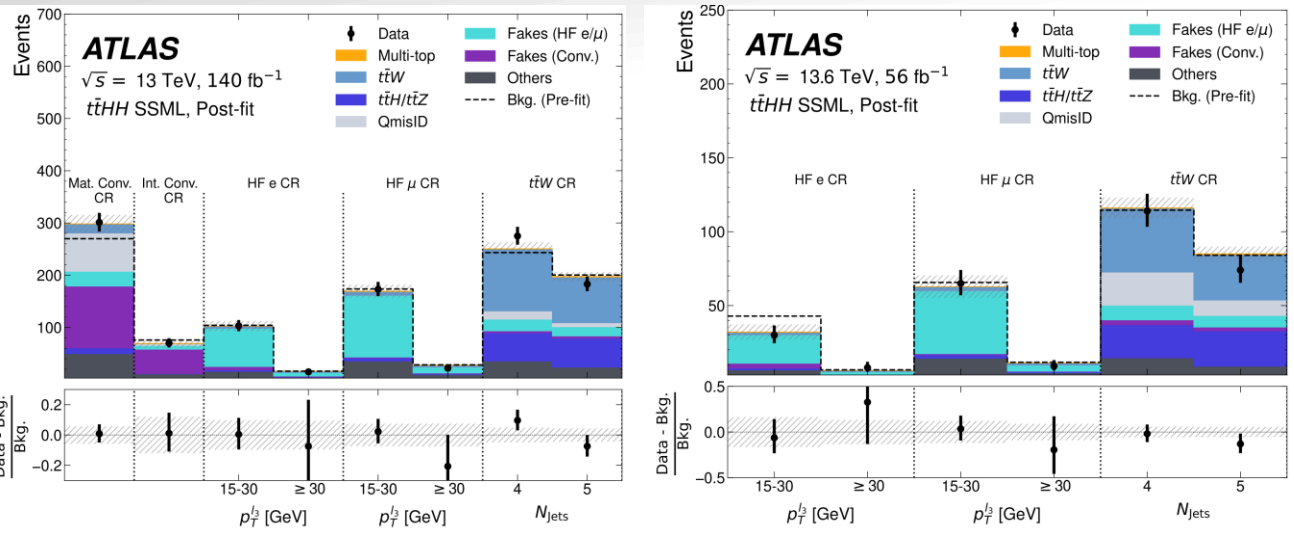


POST-FIT RESULTS

First-ever measurement

Control Regions

95% CLs limit
 $\mu_{SSML} < 40$



- Stable Data-Driven NF especially for $t\bar{t}W$
- Run 2 & Run 3 Consistency

Background source	Normalisation factor	
	Run 2	Run 3
$t\bar{t}W$	1.04 ^{+0.21} _{-0.18}	
HF e	0.97 ^{+0.24} _{-0.22}	0.46 ^{+0.33} _{-0.26}
HF μ	0.94 ^{+0.18} _{-0.17}	1.02 ^{+0.28} _{-0.25}
Mat. Conv.	1.52 ^{+0.44} _{-0.39}	—
Int. Conv.	0.86 ^{+0.23} _{-0.20}	—

Signal Regions



$b\bar{b}\gamma\gamma$



Run: 452843

Event: 4015020738

2023-05-24 10:28:32 CEST

THE $b\bar{b}\gamma\gamma$ ANALYSIS STRATEGY

Targets the narrow Higgs resonance in the diphoton mass spectrum \rightarrow 0.3% of decays

• Background modelling

• $\gamma\gamma + jets$ continuum background

- Verified from data sidebands $m_{\gamma\gamma} \notin [120,130] \text{ GeV}$
- Model with an analytic exponential function

• Single and di-Higgs backgrounds model

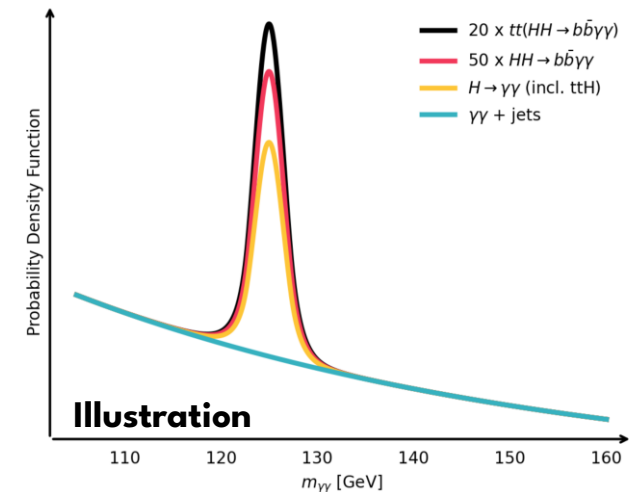
- Model with a double-sided crystal ball function (DSCB)

• Signal modelling

- MC-based modelling using DSCB
 - Resolution $\sim 1.5 \text{ GeV}$

Kinematic selections

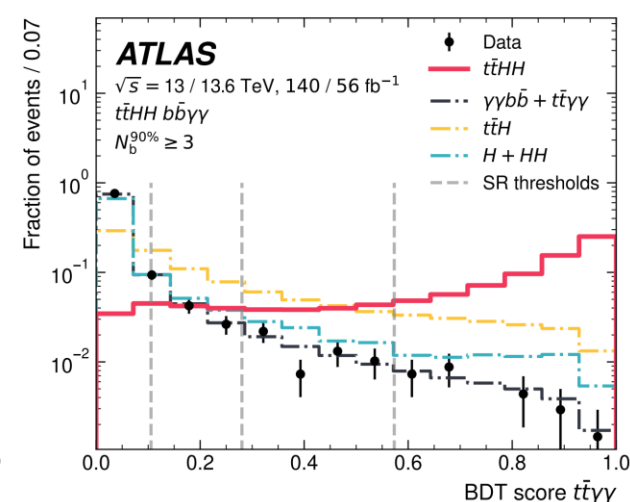
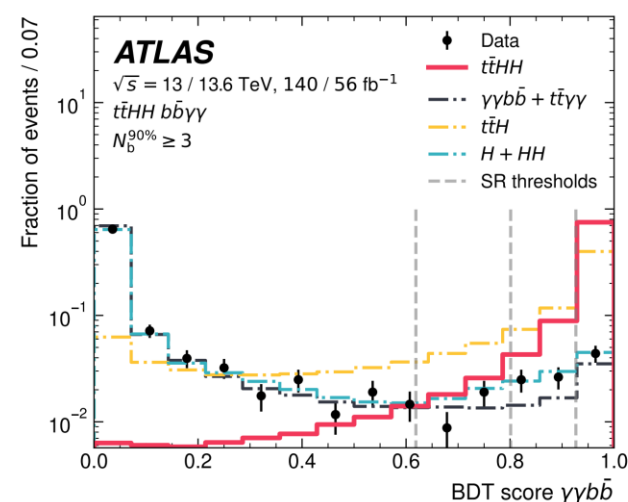
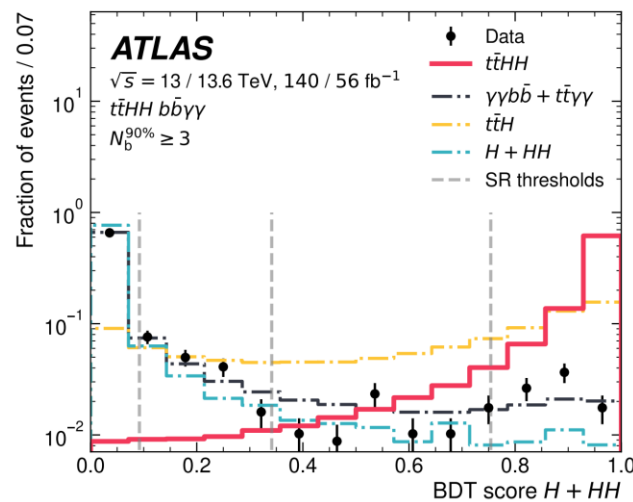
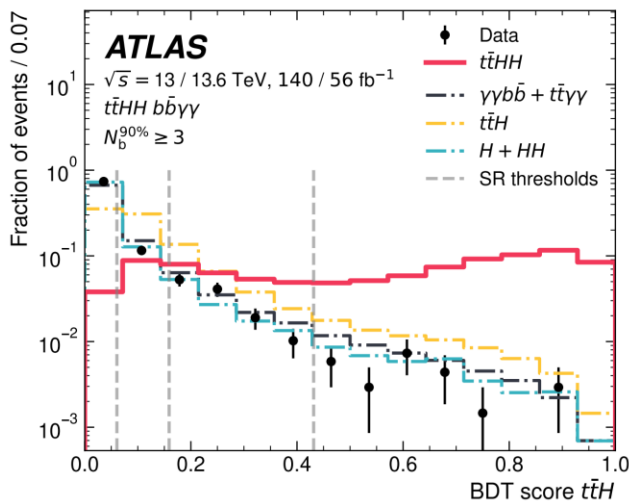
Photon relative momentum (subleading)	$m_{\gamma\gamma}/pT > 35 \text{ (25) GeV}$
b-tagged jet WP	90%



MULTIVARIATE ANALYSIS

- **Multivariate event classification**

- XGBoost with 4 BDTs trained to separate signal from major backgrounds
- Trained to maximise expected significance and require a minimum of MC events
 - 3 in $m_{\gamma\gamma} \notin [120,130]$ GeV
- Events categorized into 3 mutually exclusive regions defined using BDT scores



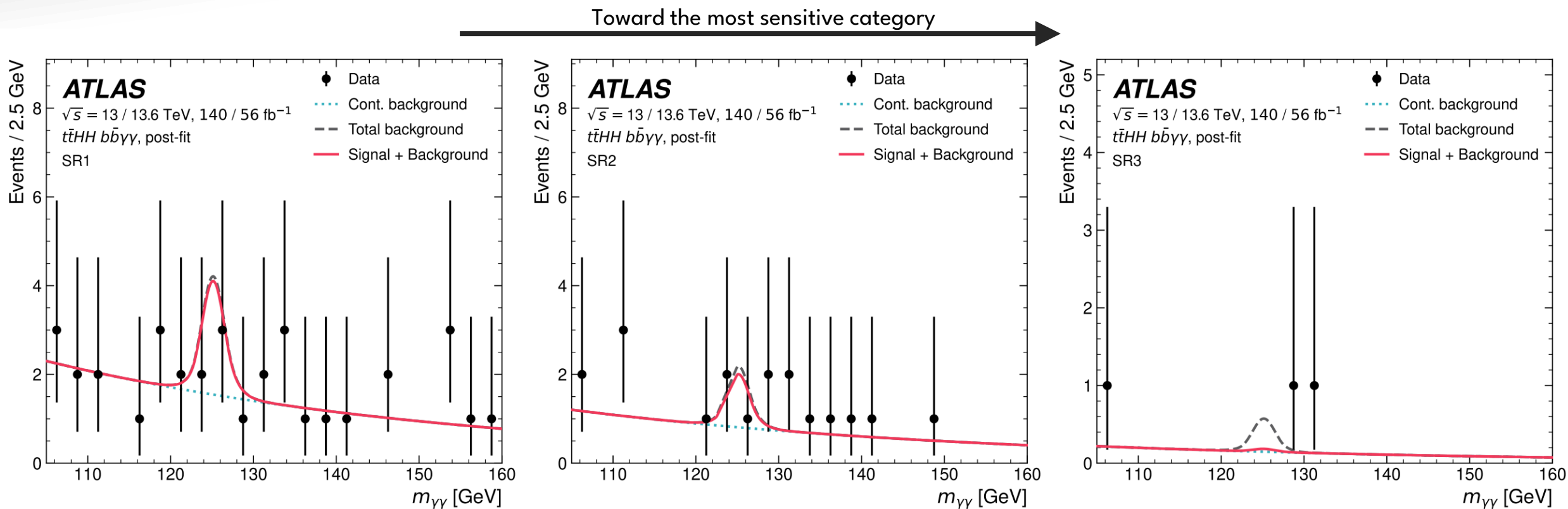
- The hardest background to isolate is $t\bar{t}H$



STATISTICAL MODEL

• Statistical inference

- Simultaneous unbinned maximum-likelihood fit to the $m_{\gamma\gamma}$ distribution across all SR



95% CLs limit

$$\mu_{b\bar{b}\gamma\gamma} < 75$$



COMBINED RESULTS

95% CLs LIMITS ON SIGNAL STRENGTH

Everything aligned with the SM...

- $\mu_{t\bar{t}HH} = 3^{+11}_{-12}$

Current best combined limit

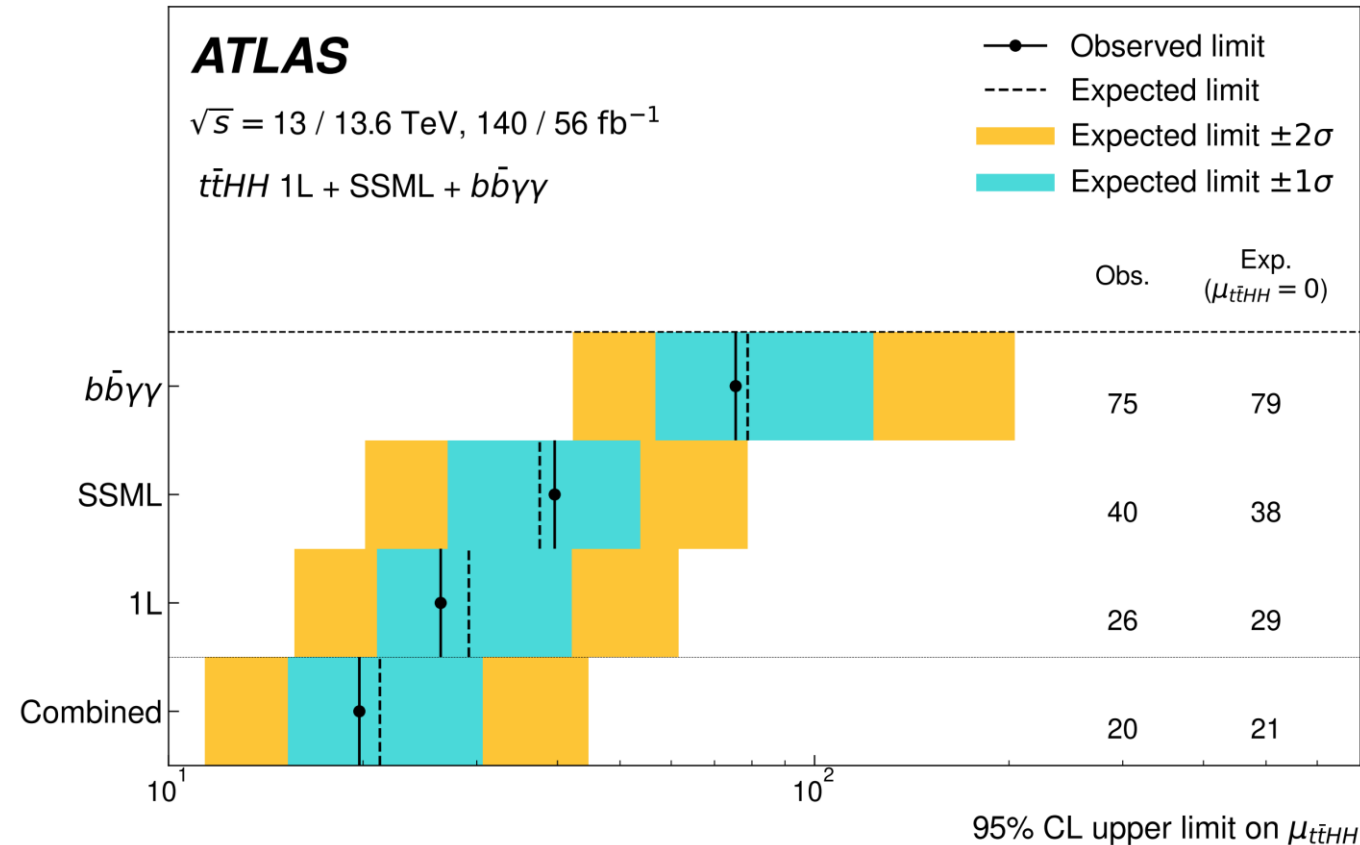
$$\mu_{t\bar{t}HH} < 20 \quad (21)$$

- Total uncertainties: A balance between the limited data and the challenges associated with modelling

CMS results [CMS-PAS-HIG-23-004]

- Closest comparison with $[b\bar{b}, WW, \tau\tau]\gamma\gamma$
- 40% less data (Run 2 only)
- 56% more signal events compared to $b\bar{b}\gamma\gamma$

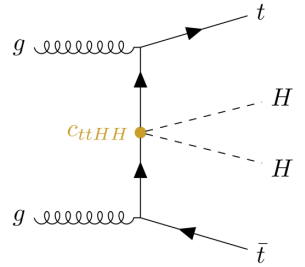
$$\rightarrow \mu_{t\bar{t}HH} < 120 \quad (86)$$



HEFT INTERPRETATION

- **Decoupling the Higgs with HEFT**

- Higgs as a gauge singlet rather than part of an $SU(2)_L$ doublet
- Decouple Higgs dynamics from the EWSB, allowing for more general deviations in its couplings



- **Constraining the Quartic Coupling**

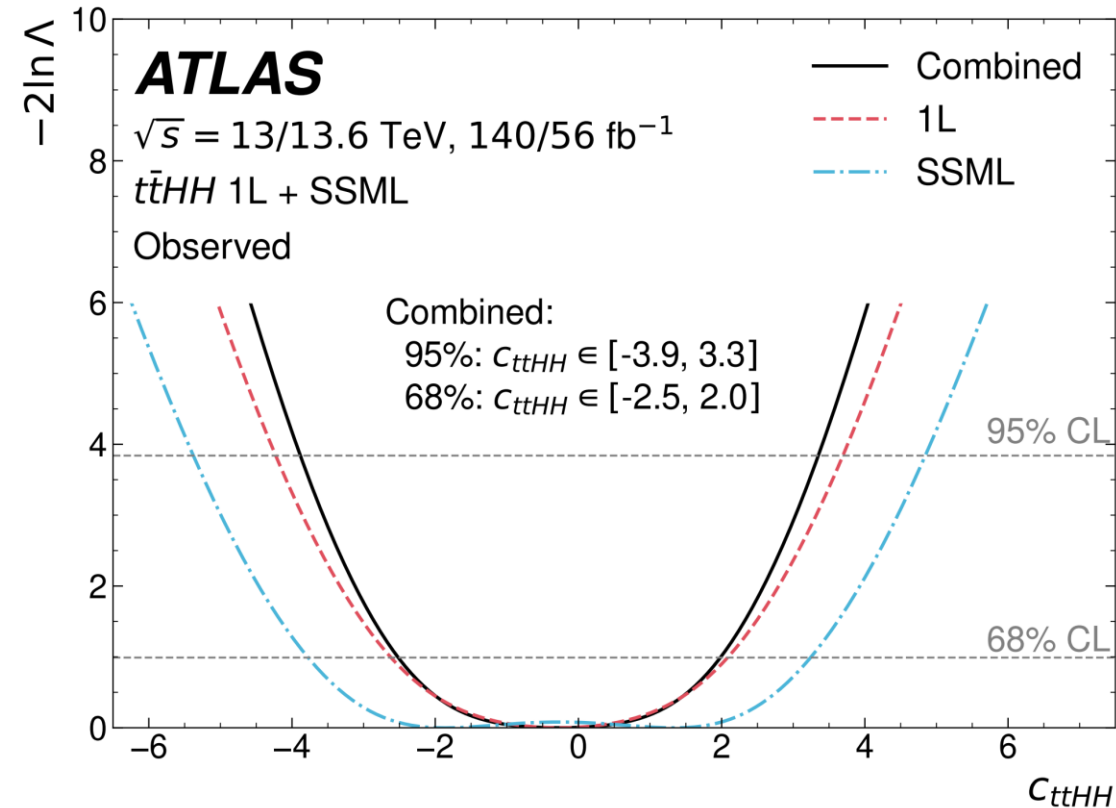
- In 1L and SSML

At 95% CL
 $c_{ttHH} \in [-3.9, 3.3]$
 (expected $[-4.1, 3.5]$)

Obs. 95% limits on c_{ttHH} (expected)

Results

[-8.0, 7.5] ([-7.4, 6.9])	CMS $t\bar{t}HH$ [CMS-PAS-HIG-23-004]
[-0.19, 0.70] ([-0.27, 0.66])	ATLAS HH comb. [arXiv:2406.09971]
[-0.29, 0.63] ([-0.27, 0.56])	CMS HH comb. [arXiv:2510.07527]

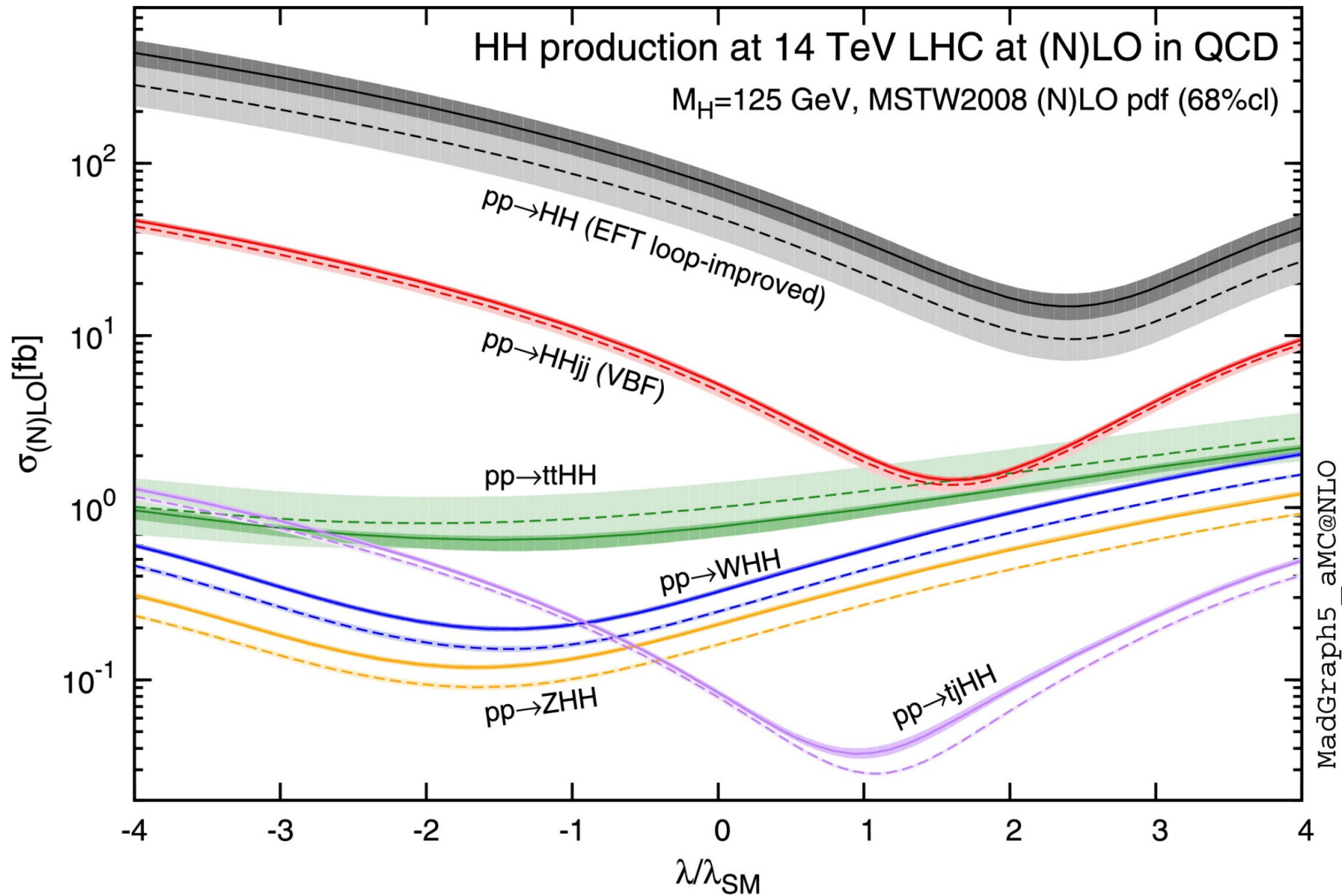


CONCLUSION

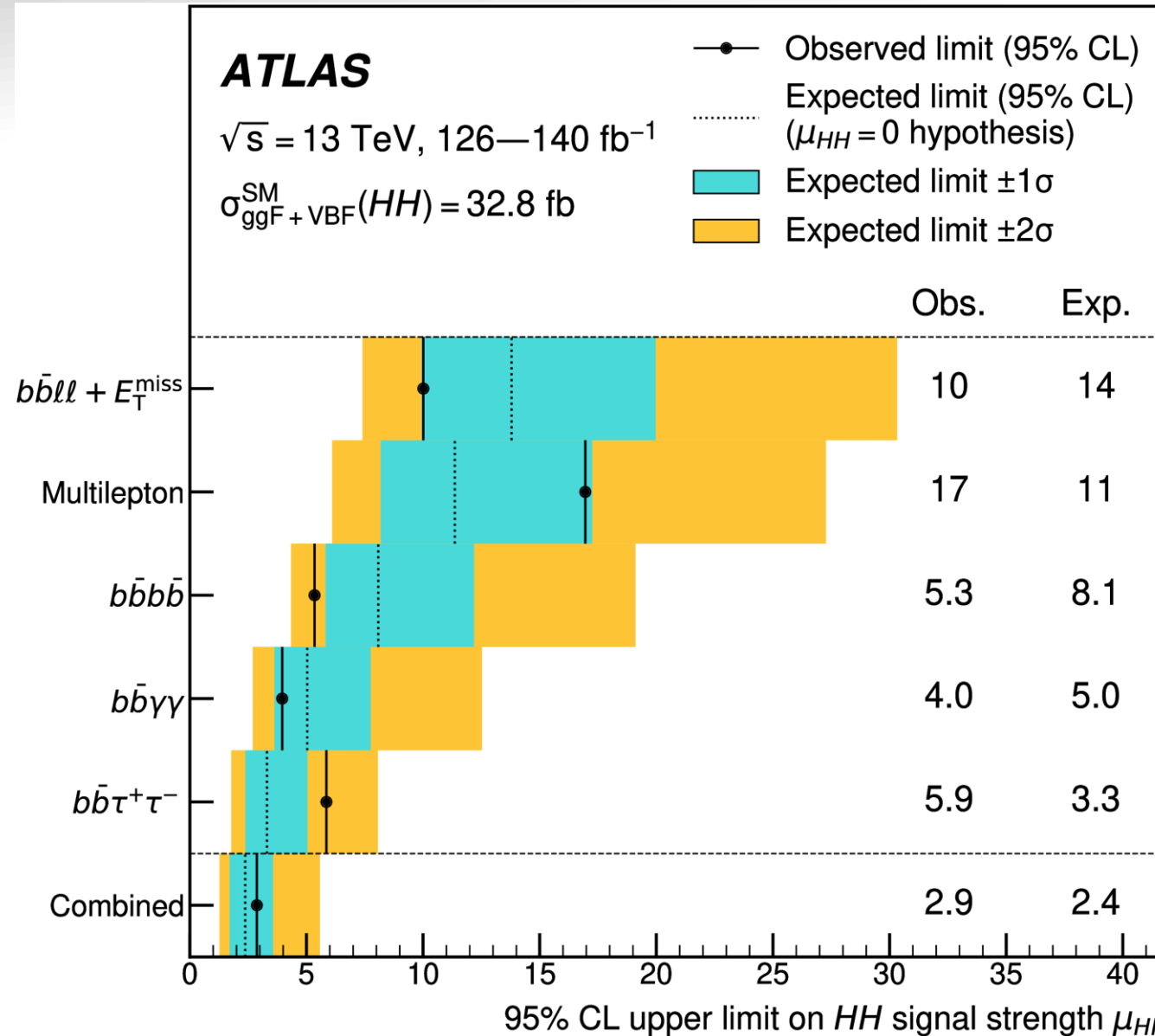
- **The first ATLAS search for non-resonant $t\bar{t}HH$**
 - Combined Run 2 (13 TeV) and Run 3 (13.6 TeV) ATLAS data
 - 3 complementary final states (1L, SSML, and $b\bar{b}\gamma\gamma$)
 - Overcoming Irreducible backgrounds & using state-of-the-art ML
- **A Probe for New Physics**
 - Direct bounds on the HEFT top-Higgs quartic coupling $c_{t\bar{t}HH}$ set
- **Our constraints are promising**
 - Faster cross-section growth than the ggF and VBF modes

BACKUP

CROSS-SECTION VS κ_λ



SIGNAL STRENGTH $ggF+VBF$ HH



BEST FITTED PARAMETERS

Channel	Best fit $\mu_{t\bar{t}HH}$
1L	-5^{+15}_{-15}
SSML	5^{+17}_{-21}
$b\bar{b}\gamma\gamma$	-13^{+35}_{-6}
Combination	-3^{+11}_{-12}

Signal strengths

Background source	Normalisation factor	
	Run 2	Run 3
$t\bar{t} + 1b$	$1.18^{+0.40}_{-0.35}$	
$t\bar{t} + 2b$	$0.91^{+0.11}_{-0.10}$	
$t\bar{t}W$	$1.04^{+0.21}_{-0.18}$	
HF e	$0.97^{+0.24}_{-0.22}$	$0.46^{+0.33}_{-0.26}$
HF μ	$0.94^{+0.18}_{-0.17}$	$1.02^{+0.28}_{-0.25}$
Mat. Conv.	$1.52^{+0.44}_{-0.39}$	—
Int. Conv.	$0.86^{+0.23}_{-0.20}$	—

Normalisation factors



BACKGROUNDS

- **Dominant Backgrounds per channel**

Channel	Backgrounds Involved
1L (Single Lepton)	$t\bar{t}$ + heavy flavor ($t\bar{t} + 1b$, $t\bar{t} + 2b$, $t\bar{t} + \geq 3b$, $t\bar{t} + \geq 1c/l$), $t\bar{t}V$, $t\bar{t}H$, Multi-top ($t\bar{t}t\bar{t}$, $t\bar{t}t$), and V +jets
SSML (Multilepton)	$t\bar{t}W$, $t\bar{t}t\bar{t}$ (Multi-top), $t\bar{t}Z$, $t\bar{t}H$, Diboson/Triboson (VV , VVV), and instrumental backgrounds: <i>QmisID</i> (charge misidentification) and <i>Fakes</i> (non-prompt leptons)
$b\bar{b}\gamma\gamma$ (Diphoton)	Continuum ($\gamma\gamma + \text{jets}$, $\gamma + \text{jet/dijet fakes}$, $t\bar{t}\gamma\gamma$), resonant single Higgs ($ggF/VBF/VH/t\bar{t}H$), and di-Higgs processes ($ggF/VBF HH$)

- **Detector Simulation**

- Full GEANT4 simulation of the ATLAS detector or a fast simulation using parameterized calorimeter showers

- **Systematic Variations**

- Comparing nominal samples to alternatives like HERWIG 7 for parton showering or varying the h_{damp} parameter in POWHEG.



SIMULATED PROCESSES

Process	Generator	ME order	Parton Shower	PDF set	Tune
$t\bar{t}HH$	MG5	LO	PYTHIA8	NNPDF2.3lo	A14
$t\bar{t}$ (5FS)	PowHEGBox	NLO	PYTHIA8	NNPDF3.0nlo	A14
$t\bar{t}t\bar{t}$	MG5_AMC	NLO	PYTHIA8	NNPDF3.0nlo	A14
$t\bar{t}t$	MG5_AMC	LO	PYTHIA8	NNPDF2.3lo	A14
$t\bar{t}W$	SHERPA	MEPS@NLO	SHERPA	NNPDF3.0nnlo	SHERPA
$t\bar{t}Z$	MG5_AMC	NLO	PYTHIA8	NNPDF3.0nnlo	A14
$t\bar{t}WW$	MG5_AMC (MG5)	LO	PYTHIA8	NNPDF3.0nlo	A14
$t\bar{t}WZ, t\bar{t}WH, t\bar{t}ZZ$	MG5	LO	PYTHIA8	NNPDF2.3lo	A14
tW	PowHEGBox	NLO	PYTHIA8	NNPDF3.0nlo	A14
tZ	MG5_AMC	LO	PYTHIA8	NNPDF3.0NL0nf4	A14
$t(q)b$ (t -channel)	PowHEGBox	NLO	PYTHIA8	NNPDF3.0NL0nf4	A14
$t(q)b$ (s -channel)	PowHEGBox	NLO	PYTHIA8	NNPDF3.0nlo	A14
tWZ, tHq, tHW	MG5_AMC	NLO	PYTHIA8	NNPDF3.0nlo	A14
$V/VV/VVV$ + jets	SHERPA	MEPS@NLO†	SHERPA	NNPDF3.0nlo	SHERPA
$\gamma\gamma$ + jets	SHERPA	NLO	SHERPA	NNPDF3.0nnlo	A14
$\gamma\gamma + t\bar{t}$	MG5	LO	PYTHIA8	NNPDF2.3lo	A14
ggF H	NNLOPS [58, 59]	NLO	PYTHIA8	PDF4LHC15	AZNLO (A14)
VBF H	PowHEGBox	NLO	PYTHIA8	PDF4LHC15 (PDF4LHC21)	AZNLO (A14)
VH	PowHEGBox	NLO	PYTHIA8	PDF4LHC15 (PDF4LHC21)	AZNLO (A14)
$t\bar{t}H$	PowHEGBox	NLO	PYTHIA8	NNPDF3.0nlo (PDF4LHC21)	A14
ggF HH	PowHEGBox	NLO	PYTHIA8	PDF4LHC21	A14
VBF HH	MG5	NLO	PYTHIA8	NNPDF3.0nlo	A14

† For the subdominant $gg \rightarrow VV$ contribution, the ME calculation is at leading order.



MULTIVARIATE ANALYSIS & STATISTICAL MODEL (1L)

• Transformer-based signal isolation

- Classification performed using a Graph Attention Network (GAT) Based on transformer attention mechanisms
- Trained to distinguish $t\bar{t}HH$ signal and $t\bar{t}$ -related backgrounds in SR
- Inputs include lepton and E_T^{miss} , selected jet kinematics, b-tagging scores (w_{PCBT})

• Simultaneous fit strategy

- Signal strength extracted with a simultaneous binned maximum-likelihood fit across signal and control regions

• Fit observables

- Signal regions ($5b_{Hi}, 6b$)
 - Transformer discriminant D_{1L}
- Control regions ($4b_{Hi}, 5b_{Lo}$)
 - Sum of b -tagging scores
 - Different truth-flavor components have different b -tagging score distributions
 - This variable allows the data to separate and constrain the different fractions of the $t\bar{t}$ background

Region	Type	$N_b^{85\%}$	$N_b^{77\%}$	Fit variable
$4b_{Hi}$	CR	4	4	$\sum_{\text{jet}} w_{PCBT}$
$5b_{Lo}$	CR	5	≤ 4	$\sum_{\text{jet}} w_{PCBT}$
$5b_{Hi}$	SR	5	5	Transformer output
$6b$	SR	≥ 6	–	Transformer output



MULTIVARIATE ANALYSIS AND STATISTICAL MODEL (SSML)

• Transformer-based event classification

- Similar GAT as 1L
- 3-class training: $t\bar{t}HH$ vs multi-top vs other backgrounds
- D_{SSML} isolates the signal while controlling the large uncertainties on multi-top production

$$D_{SSML} = \ln \left(\frac{0.2 \cdot p_{\text{multi-top}} + 0.8 \cdot p_{\text{others}}}{p_{t\bar{t}HH}} \right)$$

• Statistical inference

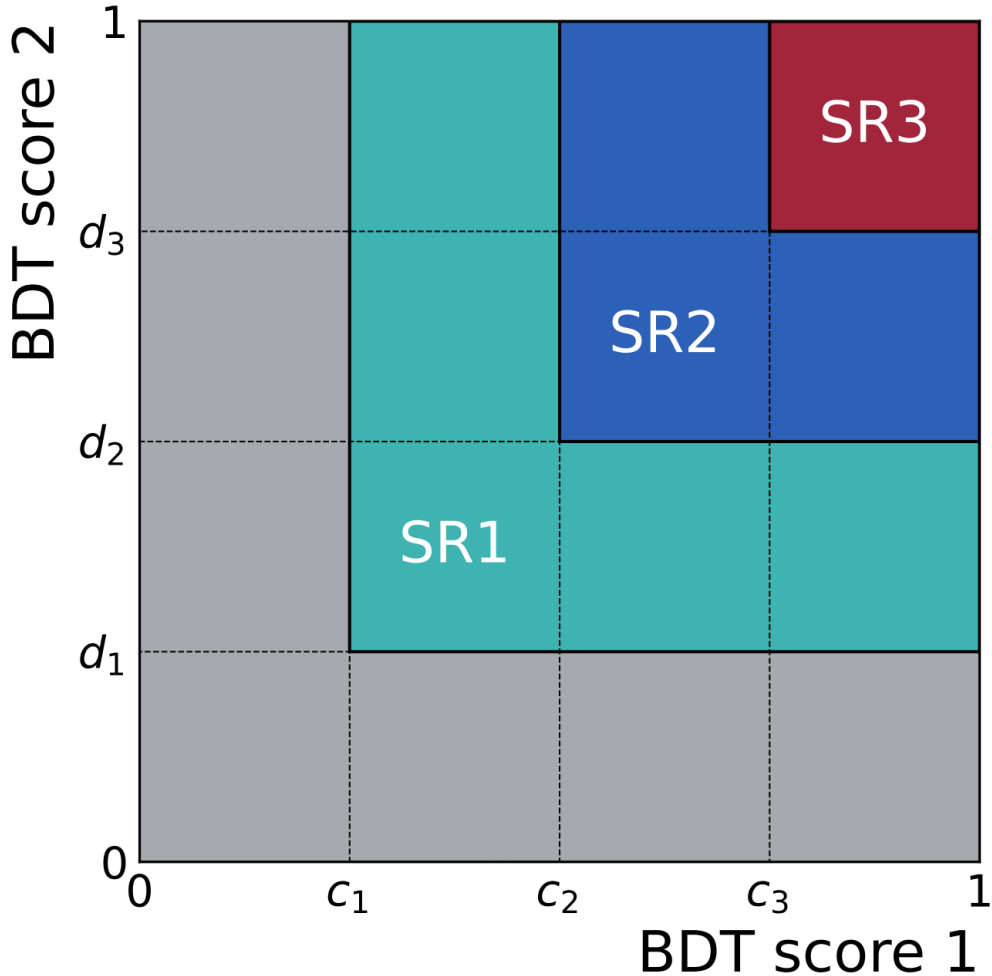
- Binned simultaneous profile-likelihood fit across the signal/control region regions
- Signal region:
 - Transformer discriminant
- Control regions
 - Kinematic variables

Control Region	Channel	N_j	$N_b^{85\%}$	Other selection	Fit variable
$t\bar{t}W$	SS2L $e\mu, \mu\mu$	≥ 4	≥ 2	$p_T^{\ell_2} > 25 \text{ GeV}, \eta(e) < 1.5$ If $N_b^{85\%} = 2$: $H_T^{\text{all}} < 400 \text{ GeV}$ or $N_j < 6$ If $N_b^{85\%} \geq 3$: $H_T^{\text{all}} < 400 \text{ GeV}$	N_j
Int. Conv.	SS2L $ee, e\mu$	$4 \leq N_j < 6$	≥ 1	Only one e from $\gamma^* \rightarrow ee$ No e from $\gamma \rightarrow ee$	N_{events}
Mat. Conv.	SS2L $ee, e\mu$	$4 \leq N_j < 6$	≥ 1	Only one e from $\gamma \rightarrow ee$ No e from $\gamma^* \rightarrow ee$	N_{events}
HF μ	3L $e\mu\mu, \mu\mu\mu$	≥ 1	$= 1$	$E_T^{\text{miss}} > 35 \text{ GeV}$ $100 < H_T^{\text{all}} < 275 \text{ GeV}$ Total lepton charge = ± 1	$p_T^{\ell_3}$
HF e	3L $eee, ee\mu$	≥ 1	$= 1$	$E_T^{\text{miss}} > 35 \text{ GeV}$ $100 < H_T^{\text{all}} < 275 \text{ GeV}$ Total lepton charge = ± 1	$p_T^{\ell_3}$

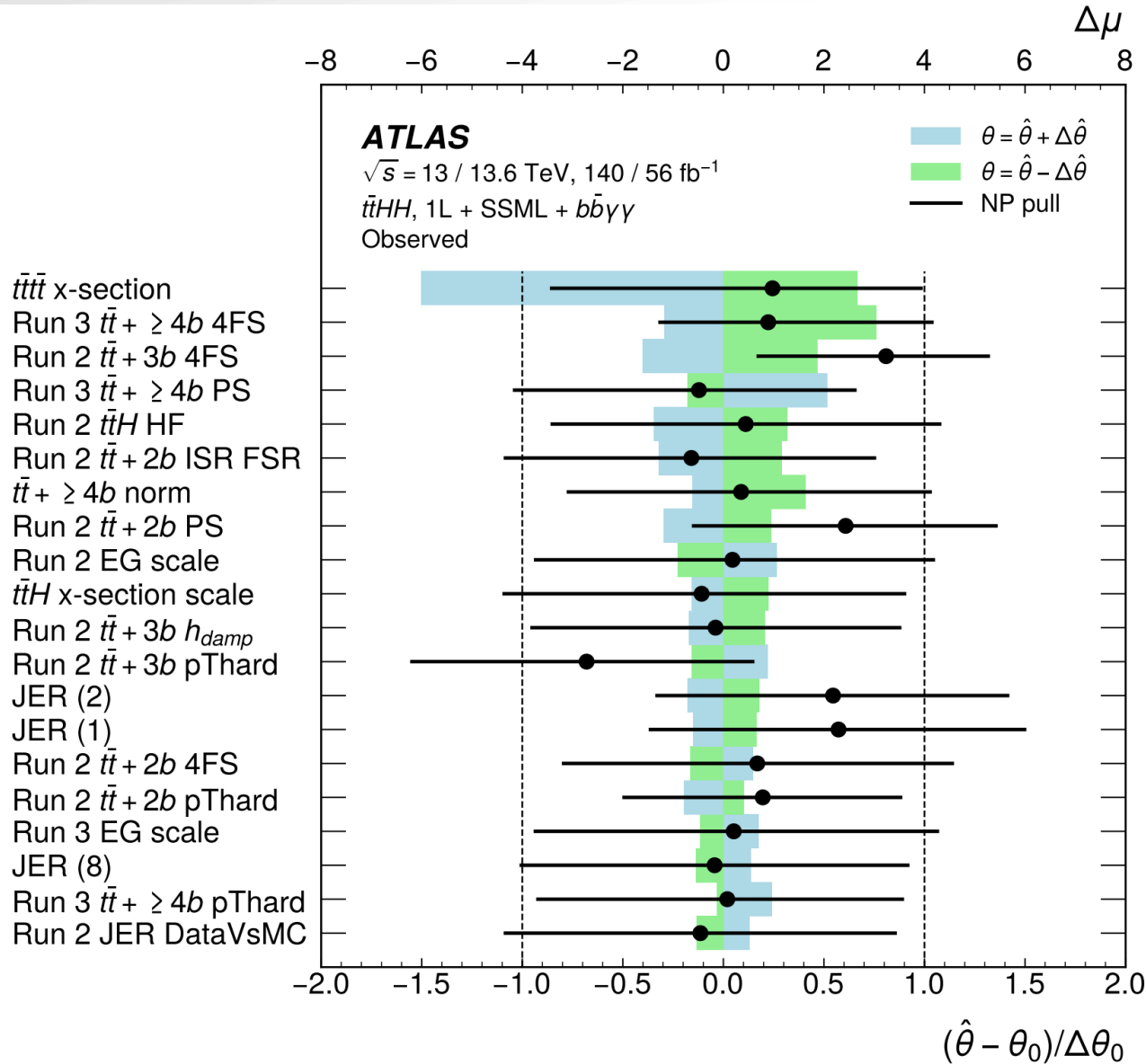


MUTUAL EXCLUSION FOR BDT CATEGORIES

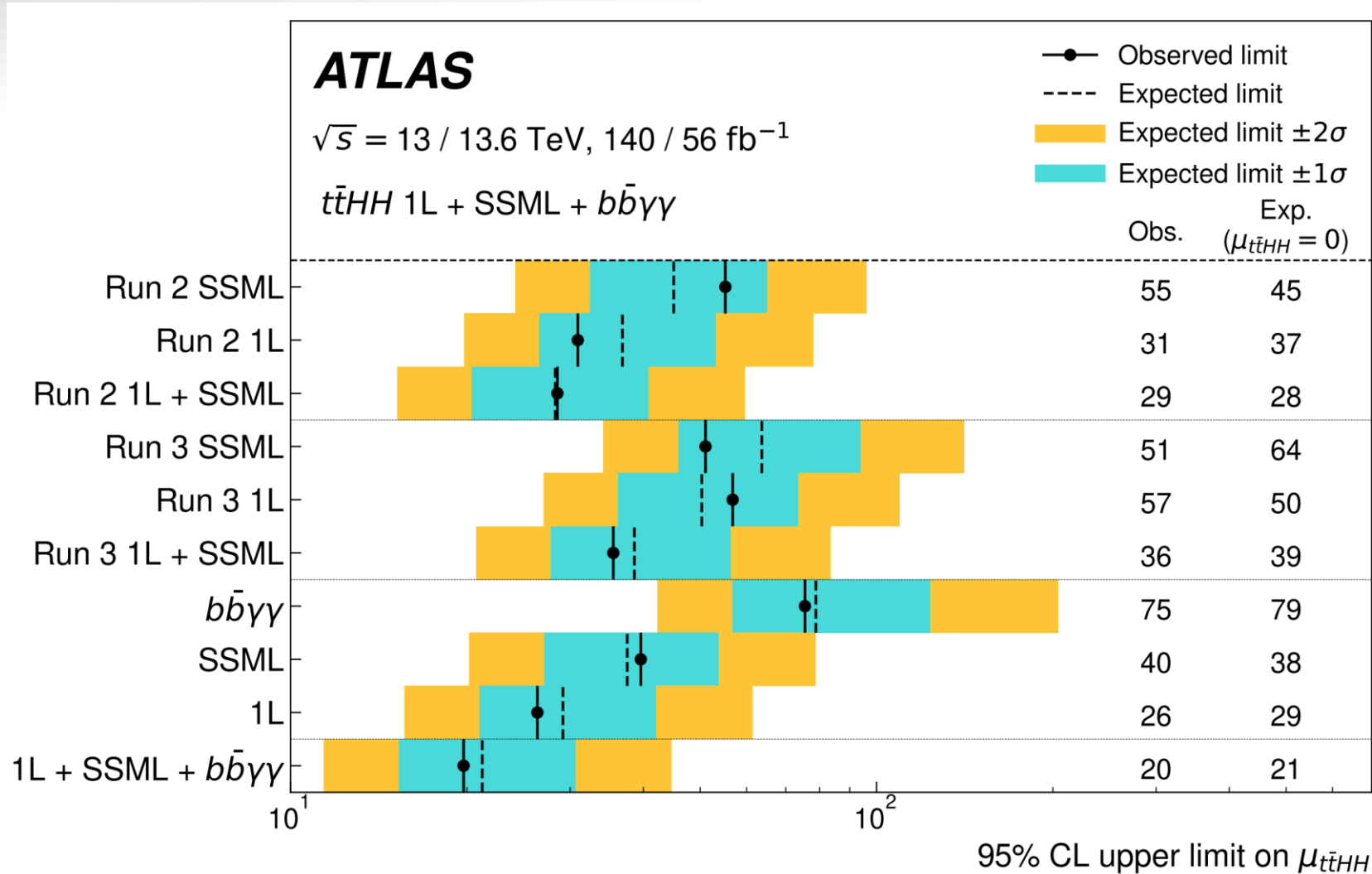
- Illustration



LEADING SYSTEMATICS



LIMITS BREAKDOWN PER RUN



TOTAL UNCERTAINTIES

A balance between the limited data and the challenges associated with modelling

- **Background modelling**

- Predicting $t\bar{t}$ production with additional HF jets remains particularly challenging
- $t\bar{t} + \geq 3b$ configuration are difficult to model

- **Normalization factors**

- Simulations often underestimate HF jet production
- Data CR used to constrain these contributions introducing additional statistical uncertainty

- **Statistical uncertainty from Data**

- The production remains extremely rare

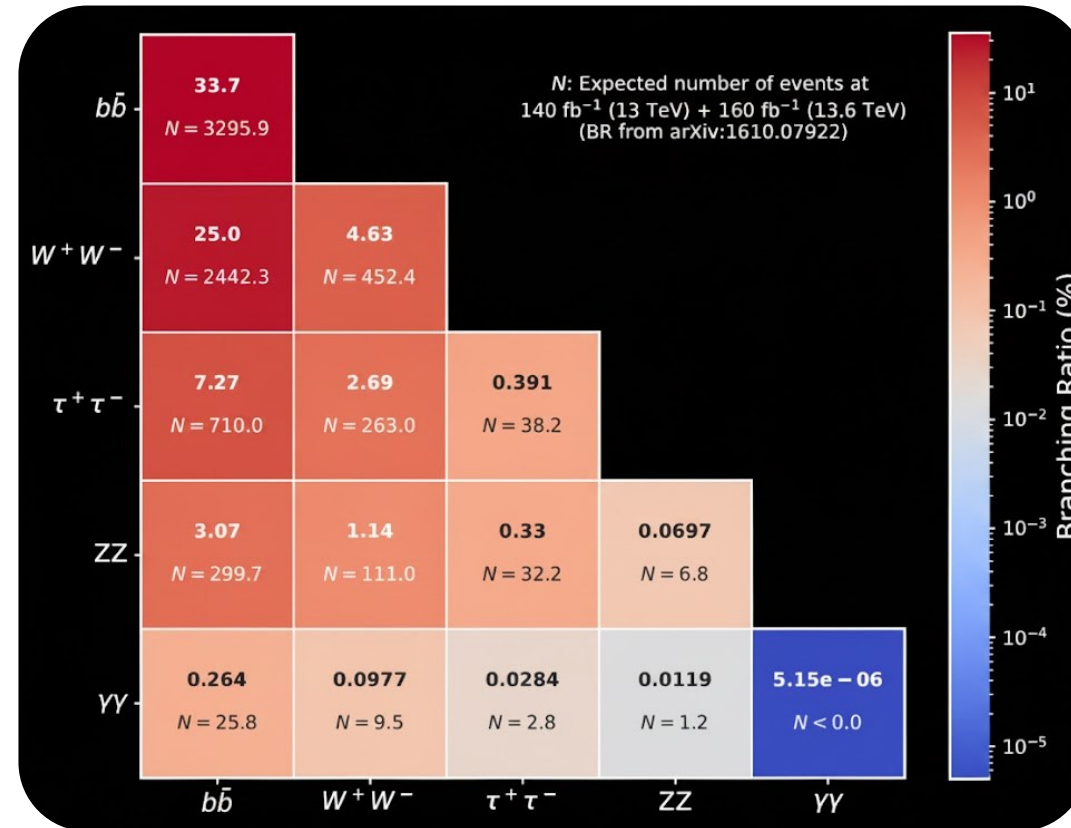
- **Instrumental and detector effects**

- Jet Energy Scale / Resolution
 - Effects induced by the multiplicity
- Flavour Tagging
 - Possible misidentification of light-flavor jets as b-jets

Uncertainty Source	Observed	Expected
Signal modelling	(+0.9, -1.8)	(+1.3, -1.0)
Background modelling	(+6.8, -8.2)	(+5.7, -6.2)
$t\bar{t} + \text{jets}$	(+5.3, -6.5)	(+4.7, -5.0)
$t\bar{t}\bar{t}\bar{t}$	(+4.6, -6.4)	(+2.9, -4.0)
$t\bar{t}H$	(+2.1, -1.6)	(+2.0, -1.9)
others	(+0.9, -0.7)	(+0.9, -0.8)
MC statistical	(+2.8, -3.7)	(+2.5, -2.7)
Detector systematic	(+2.2, -3.4)	(+1.9, -1.5)
Total systematic	(+8.3, -9.4)	(+7.3, -7.4)
Data statistical	(+7.2, -6.8)	(+7.2, -6.7)
Total	(+11.0, -11.6)	(+10.3, -10.0)



HH BRANCHING RATIO



STATISTICAL MODEL

probability to observe n_c events when expecting $N_c(\theta)$
→ affect **event yields** (signal strength μ , cross-section)

Gaussian/log-normal priors on systematics.
→ ensures uncertainties on JES, PDFs, etc. are included.

$$\mathcal{L} = \prod_c \left(\text{Pois}(n_c | N_c(\vec{\theta})) \cdot \prod_{i=1}^{n_c} f_c(m_{\gamma\gamma}^i, \vec{\theta}) \cdot G(\vec{\theta}) \right)$$

Product over **Signal Regions**

probability density evaluated at each event's invariant mass
→ carries **mass peak and background shape information**.

